

**NASA TECHNICAL  
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**NASA TM X-1235**

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GPO PRICE \$ \_\_\_\_\_

CFSTI PRICE(S) \$ 1.00

Hard copy (HC) \_\_\_\_\_

Microfiche (MF) 50

# 653 July 65

**N66-238 62**

(ACCESSION NUMBER)

(AUTHORITY)

17

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TMX-1235

(NATIONAL AERONAUTICS AND SPACE ADMINISTRATION)

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(CONFIDENTIAL)

## **A PENDULOUS ANGLE SENSOR**

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*Moffett Field, Calif.*

**NATIONAL AERONAUTICS AND SPACE ADMINISTRATION - WASHINGTON, D. C. - MAY 1966**

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## A PENDULOUS ANGLE SENSOR

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### SUMMARY

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An improved model of a very sensitive gravity-actuated angle sensor is described. The instrument utilizes a potentiometer whose wiper position relative to a pendulum-suspended resistance element is proportional to the angle. A precision of  $\pm 0.02^\circ$  for a  $60^\circ$  range is achieved because the capacitively coupled wiper does not contact the resistance element and, hence, cannot introduce friction. An internal preamplifier is employed to reduce errors caused by cable capacitance, and a servo unit facilitates readout.

### INTRODUCTION

A previous report described an angle-of-attack transducer designed for use inside sting-supported wind-tunnel models. Recent mechanical improvements and the incorporation of a preamplifier in the sensor make the instrument somewhat more rugged and much less sensitive to extraneous capacitance couplings introduced in some wind-tunnel installations. The improved transducer is described in this report.

The superior performance of the earlier instrument (ref. 1) is made possible by the use of a frictionless "contact" which provides a capacitive coupling to a pendulous resistance element. An AC servo-balanced bridge provides readout and, at the same time, readjusts the grounding point of the circuit so as to maintain the capacitive contactor at zero potential relative to the cable shield and instrument housing, independent of the position of the wiper contact relative to the pendulous resistance element. Figure 1 is a diagram of the angle transducer system. The instrument has the following very desirable characteristics:

1. It is small because the reduced frictional torque makes possible a short pendulum arm and a low pendulum mass.
2. It is extremely linear because the capacitively coupled wiper is designed to average the potential of several turns of the resistance wire on the pendulous potentiometer, thereby minimizing nonlinearities resulting from turn-to-turn winding irregularities.
3. It is insensitive to temperature effects since both elements of the pendulous potentiometer are similarly affected.

Properly installed, the old instrument provided each of these advantages without any serious problems. Frequently, however, in a wind-tunnel installation, it was necessary to cut the shielded cables (used for isolating the bridge excitation leads from the sensing lead) and pass them unshielded through a bulkhead. The inherently high impedance of the contactor made the old sensor sensitive to the capacitive coupling from the poorly shielded bridge excitation leads to the sensing wiper lead and caused error currents comparable to those induced by the position error voltage (signal) through the  $2 \times 10^{-12}$  farad wiper. As a result of the reduced output impedance provided by a preamplifier, which was added internal to the recently revised sensor, these effects are essentially eliminated.

## DESCRIPTION

The angle sensing element of the instrument is a pendulum (fig. 2) consisting of a sector of a wheel with a flat coil of resistance wire mounted on the rim. This coil is formed by 1000 turns of 0.001-inch-diameter enamel-coated wire wrapped around a form 0.01 inch thick, by 0.18 inch wide, by 1.25 inches long. This coil is bent to a 0.72-inch radius and cemented to the rim of the  $80^\circ$  circular-arc segment of the pendulum, so as to be accurately concentric with the pivot axis.

Gravity causes the pendulum to rotate about the pivot axis established by hardened steel pivot bearings with spherical tips of 0.0012-inch radius. These pivots are fitted into sockets or mating depressions made by punching similar pivots into the polished hardened steel surfaces of the two pivot-shaft end supports. One of these sockets is mounted rigidly in the frame of the instrument, while the other is mounted in a plate which can be moved to adjust the pivot-bearing clearance.

The pendulum is mounted in the support frame, as shown in figure 3, so that the resistance coil is spaced within 0.003 inch of the capacitance contactor which is mounted rigidly to the lower central portion of the frame. The contactor is 0.190 inch long and 0.025 inch wide, and is shielded so that there can be essentially no capacitive coupling to the two hairsprings located on opposite sides of the pendulum concentric with the pivot shaft. The hairsprings are used to transmit the AC excitation to the pendulous resistance element.

The pendulum and its supporting frame are fitted within the case as shown in figure 4. The case is filled under vacuum with a silicone fluid of appropriate viscosity for damping. The cover to the case is equipped with rubber-diaphragm-sealed expansion chambers of sufficient volume to allow for the contraction and expansion of the damping fluid when the environmental temperature varies between the limits of  $20^\circ$  and  $200^\circ$  Fahrenheit. The cover with expansion diaphragms and retaining plugs is shown in figure 5. A composite exploded view of the angle sensor parts is shown in figure 6. The assembled angle sensor (fig. 7) is  $1\frac{7}{8}$  inches long, by  $1\frac{3}{32}$  inches high, by  $\frac{5}{8}$  inch wide, and weighs 4.1 ounces.

Mechanical differences between the old and new angle sensors are slight and pertain mainly to the manner of allowing for expansion of the damping fluid. The significant improvement in performance obtained with the new instrument was the result of modifications to the electronics. Sensitivity to the capacitive coupling introduced by poor installation practices was significantly reduced by placing a miniature low output impedance preamplifier within the sensor. A circuit which provides an adequately high input impedance (150 megohms, shunted by a capacitance of 10 picofarads) and an adequately low output impedance (8 ohms) is shown schematically in figure 8. This circuit was constructed of miniature components and packaged as shown in figure 9. The preamplifier unit was mounted next to the connector in a cavity in the rear of the angle sensor as shown in figure 10.

Vibration-induced motion of the preamplifier within the sensor causes small variations in input voltage due to the charge existing on the input circuitry and the capacitive modulation induced by the vibration. To avoid ambiguity in the output readings, the output from the preamplifier is filtered by an active band-pass filter, centered around the AC carrier frequency. The carrier power, amplification, servo control of the applied power, and indication of the sensed angle are provided by a slight modification of a standard servo unit designed at Ames Research Center.<sup>1</sup> The only modifications required involve removing the input circuitry and the 400 cps chopper, that were needed when the servo was used with resistance strain gages, and adding a preamplifier power supply.

## RESULTS

Performance of the angle transducer system is indicated by the error curve shown in figure 11. Input angles were applied by rotating the sensor on an optical dividing head having a precision of  $\pm 0.0006^\circ$ . The servo readout was adjusted to provide full-scale positive indication for a  $30^\circ$  rotation of the sensor. The angle settings of the dividing head, during an increasing and decreasing calibration cycle, were subtracted from the corresponding angular readings indicated by the servo unit, giving the error data plotted in figure 11. The errors include all electrical errors and all mechanical errors associated with the system. These include sensor nonlinearity and hysteresis, error couplings in the preamplifier, electrical errors in the servo, nonlinearity and hysteresis in the servo-balance potentiometer with its gear drive, etc. The over-all system error was found to be less than  $\pm 0.02^\circ$ . (The linearity specified by the manufacturer of the servo-balance potentiometer is  $\pm 0.05$  percent, which is equivalent to  $\pm 0.03^\circ$ .)

Circuit sensitivity to stray capacitance is primarily related to capacitive loading and coupling in the output cabling of the transducer, and depends on the position of the capacitance contactor relative to the ends of the pendulous resistor. Tests have shown that capacitors as large as  $0.01 \mu\text{f}$  introduced between any pair of transducer leads (e.g., preamplifier output, preamplifier

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<sup>1</sup>Manufactured by Metrotech Inc., Mountain View, Calif. (Model 7100 ATS).

power, bridge excitation, or ground) produce errors less than 0.1 percent in the output. Capacitors smaller than 0.003  $\mu$ f produce no measurable error.

### CONCLUSIONS

The highly linear characteristic of the capacitively coupled potentiometer, together with the newly obtained freedom from sensitivity to unwanted stray capacitances in the system installation, gives it a highly desirable combination of features: small size, high precision, and freedom from wear of the critical sensing element. These unique characteristics make the application of the device to other measurement problems an intriguing possibility.

Ames Research Center

National Aeronautics and Space Administration  
Moffett Field, Calif., Feb. 7, 1966

### REFERENCE

1. Dimeff, John; and Fryer, Thomas B.: Capacitance Pickup Measures Small Forces. Electronics, vol. 30, no. 2, Feb. 1957, pp. 143-145.

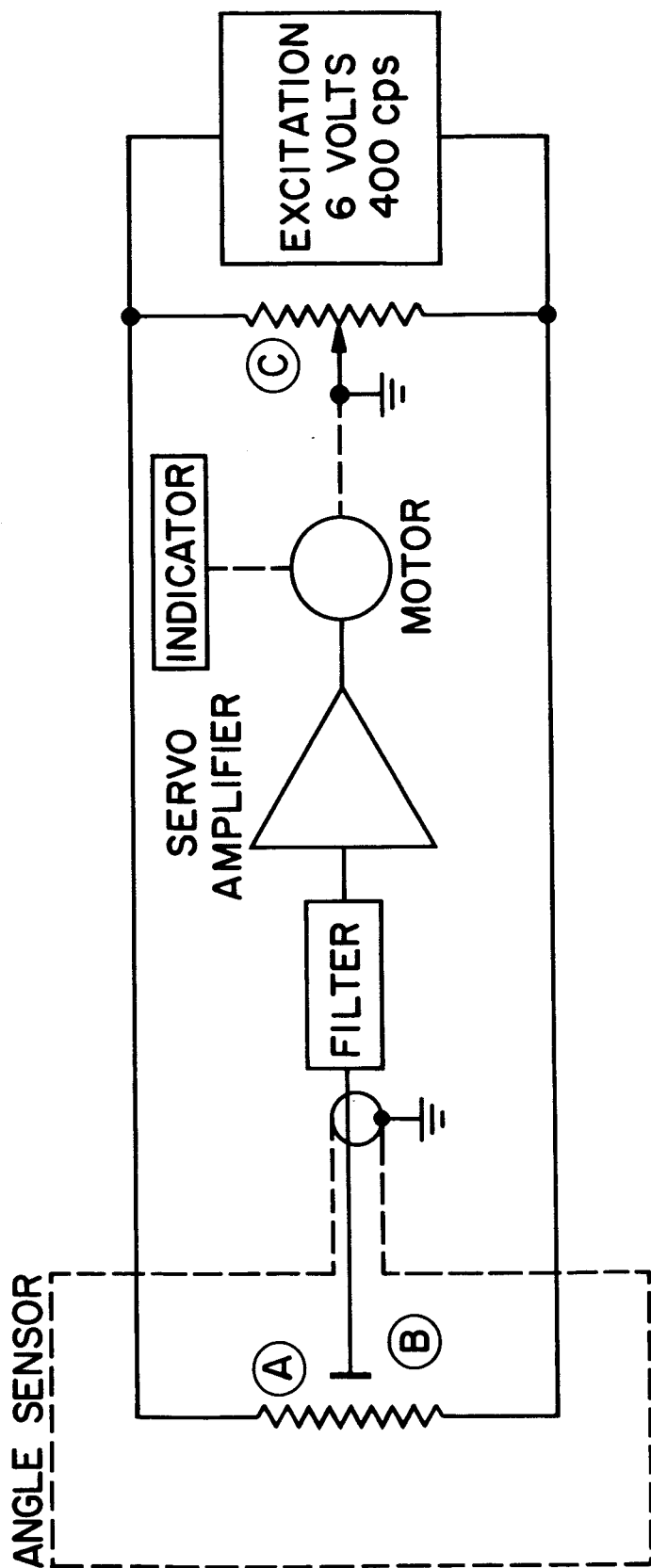
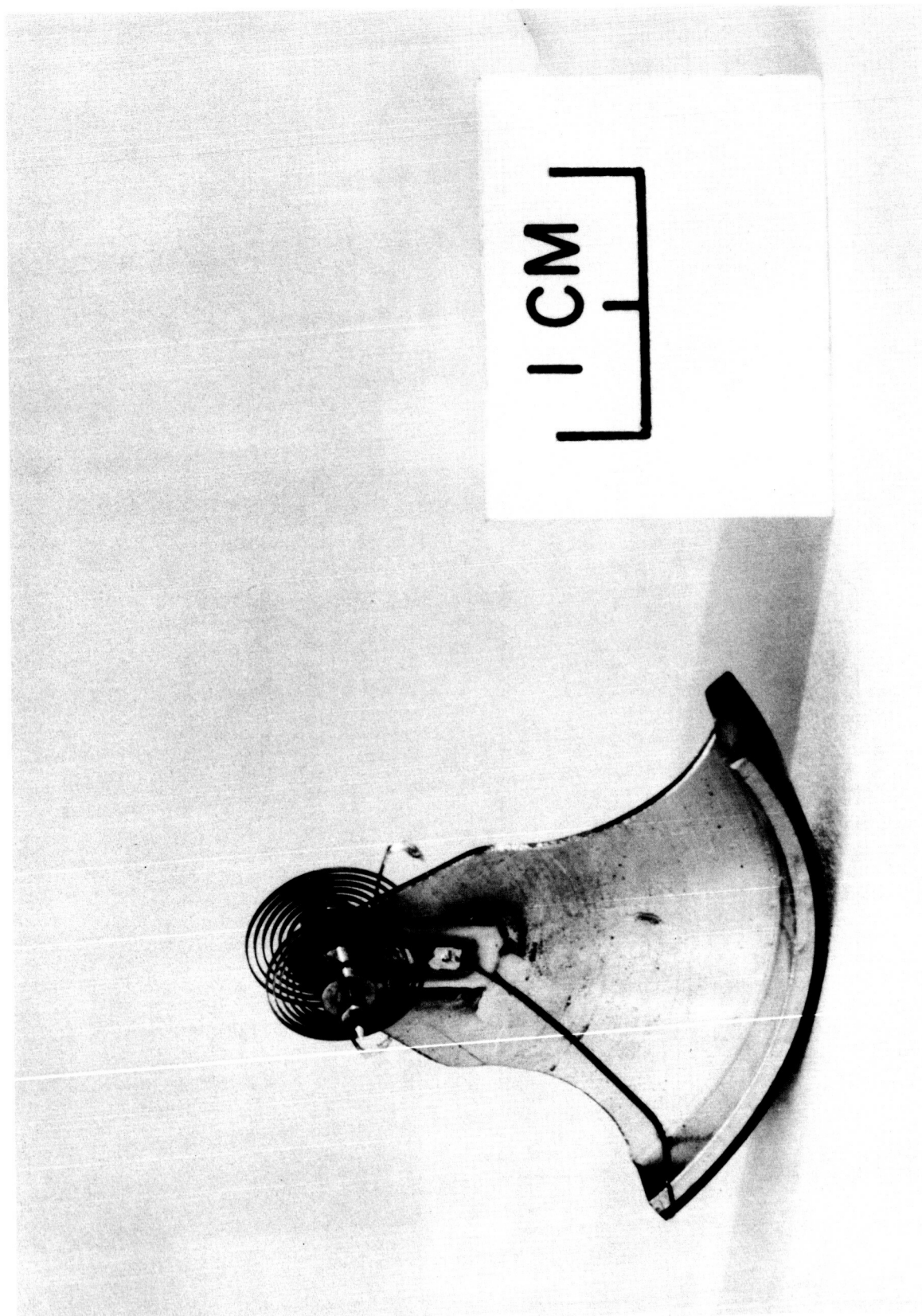
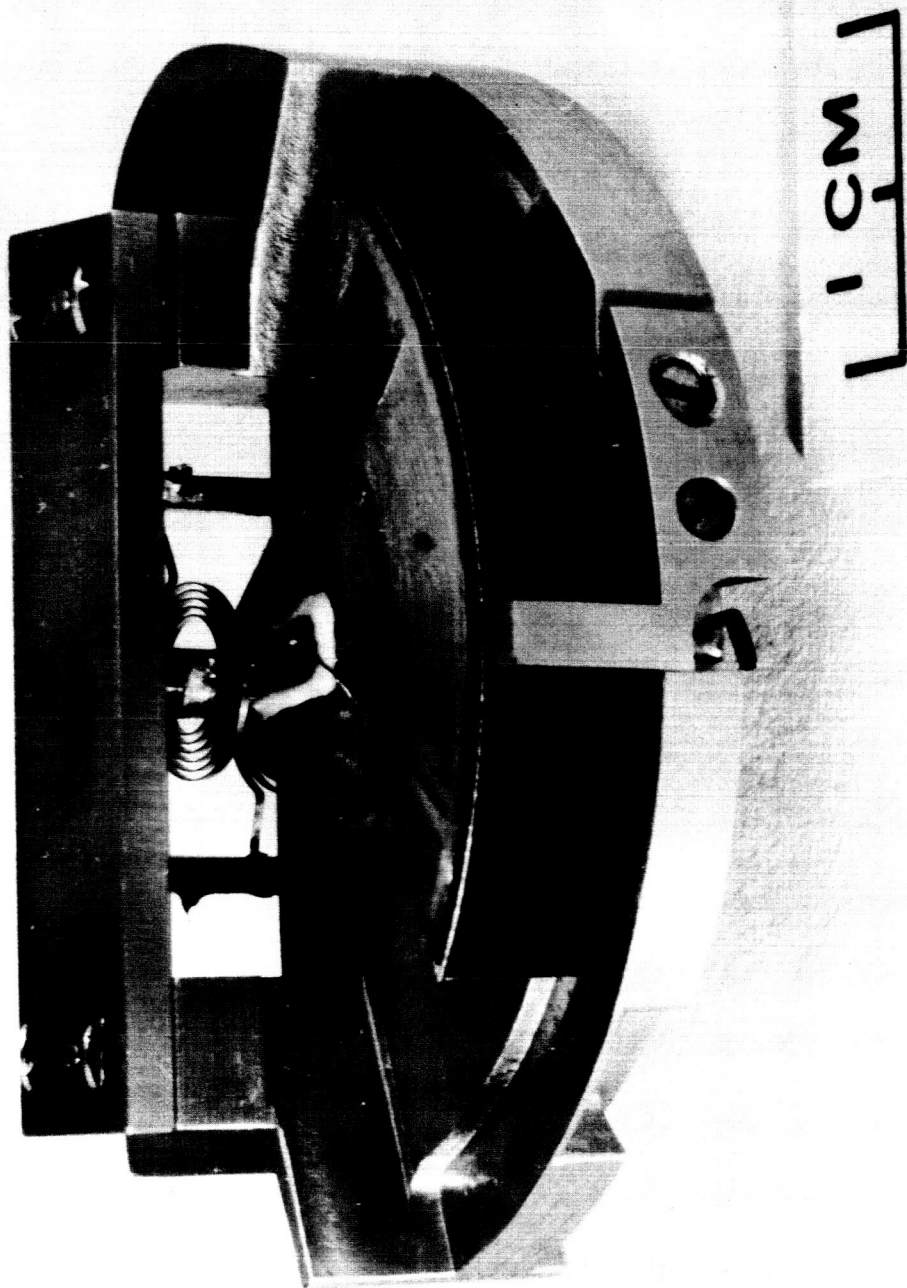


Figure 1.- Angle transducer system diagram.



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Figure 2.- Pendulum



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Figure 3.- Pendulum mounted in frame.

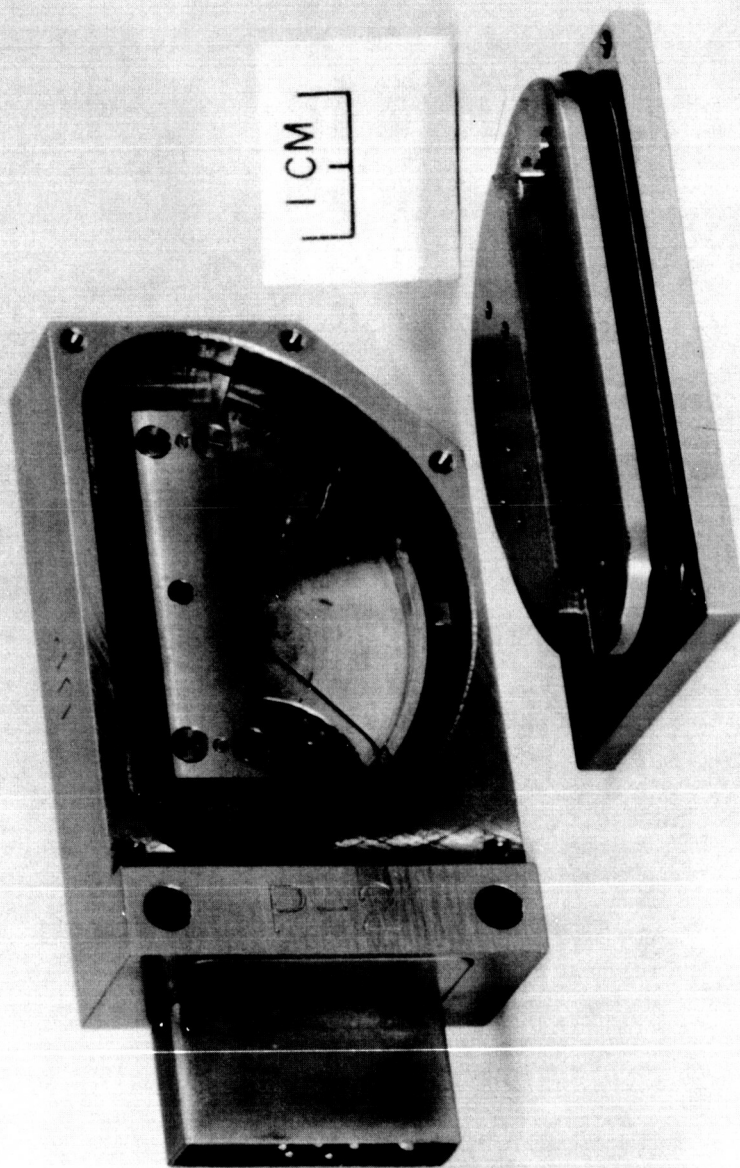


Figure 4.- Sensor assembly with cover open.

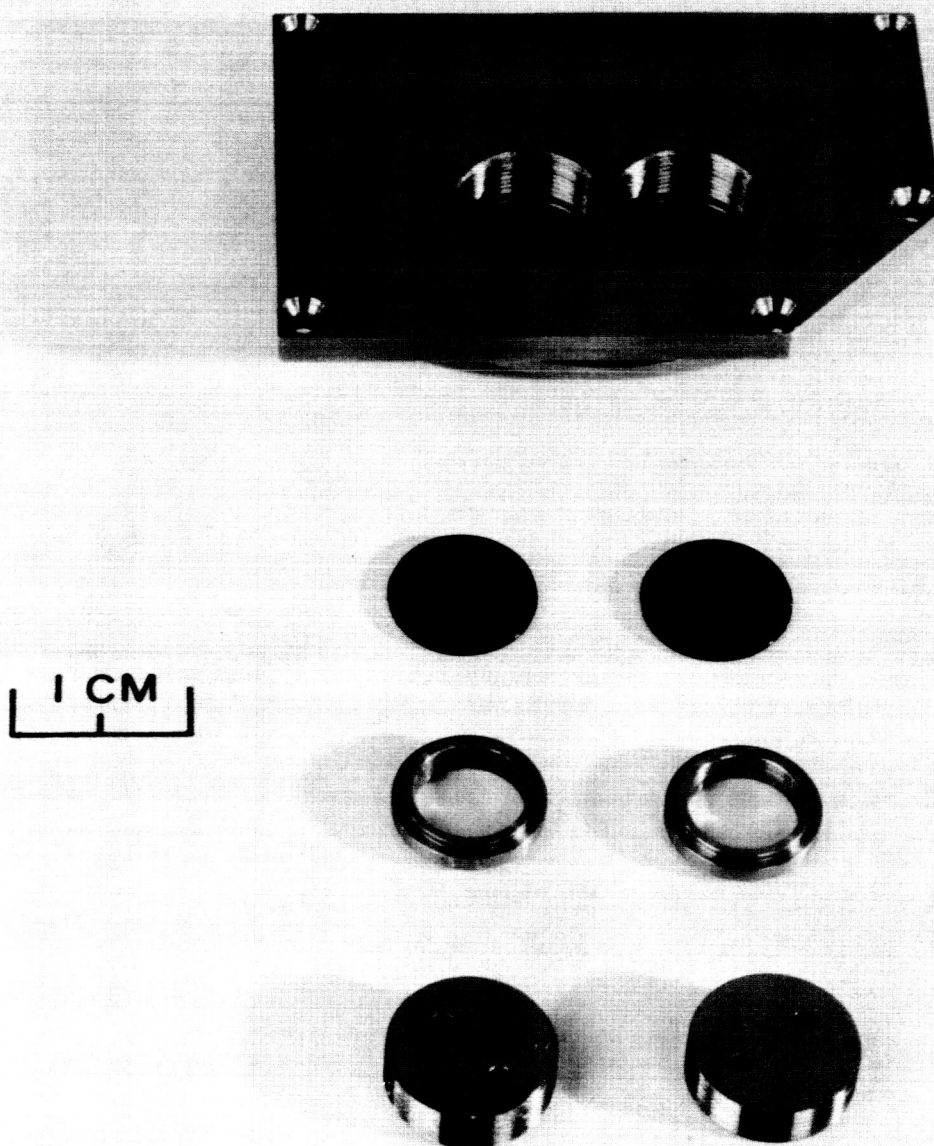
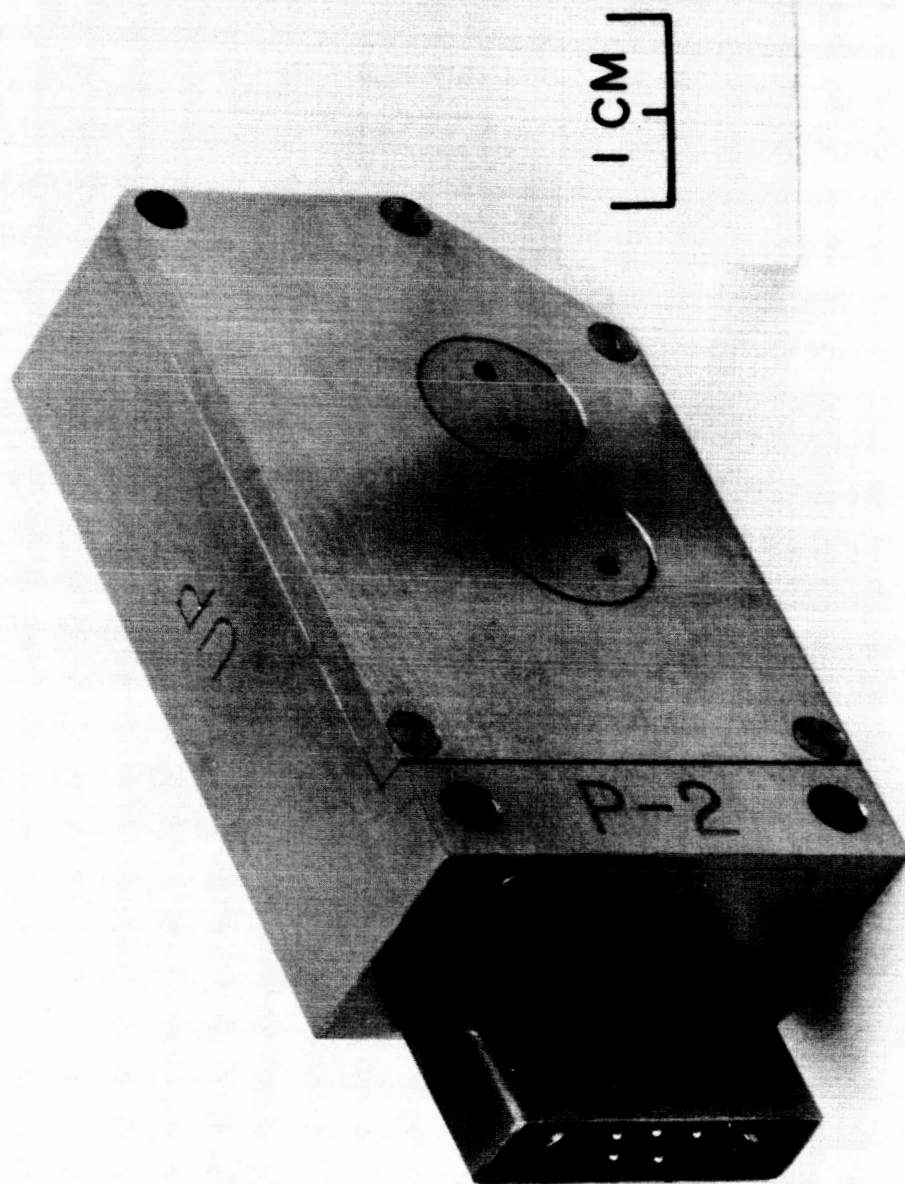


Figure 5.- Cover with expansion diaphragms.

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Figure 6.- Exploded view of parts.



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Figure 7.- Exterior view of sensor.

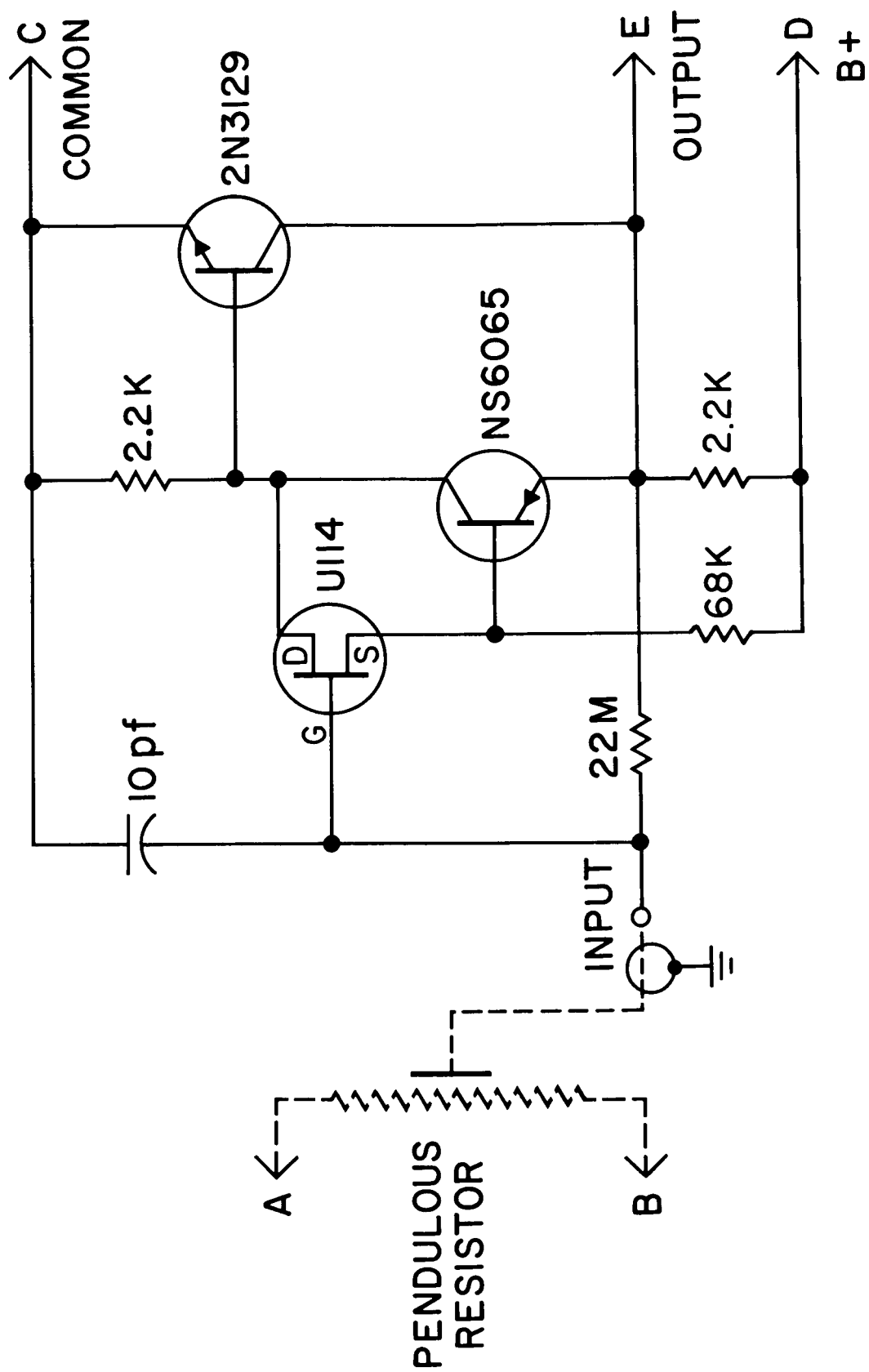


Figure 8.- Preamplifier circuit.

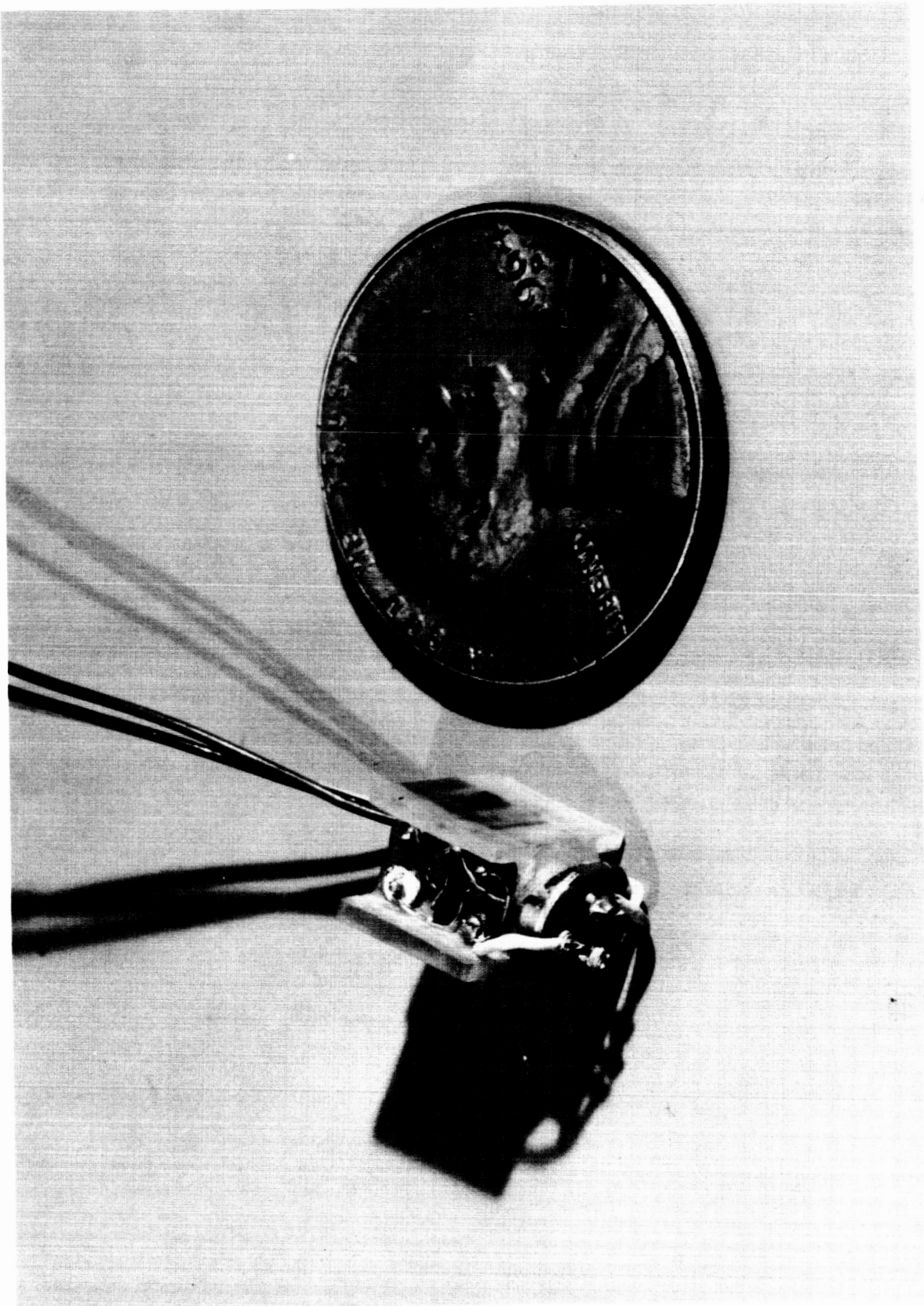


Figure 9.- Preamplifier unit.

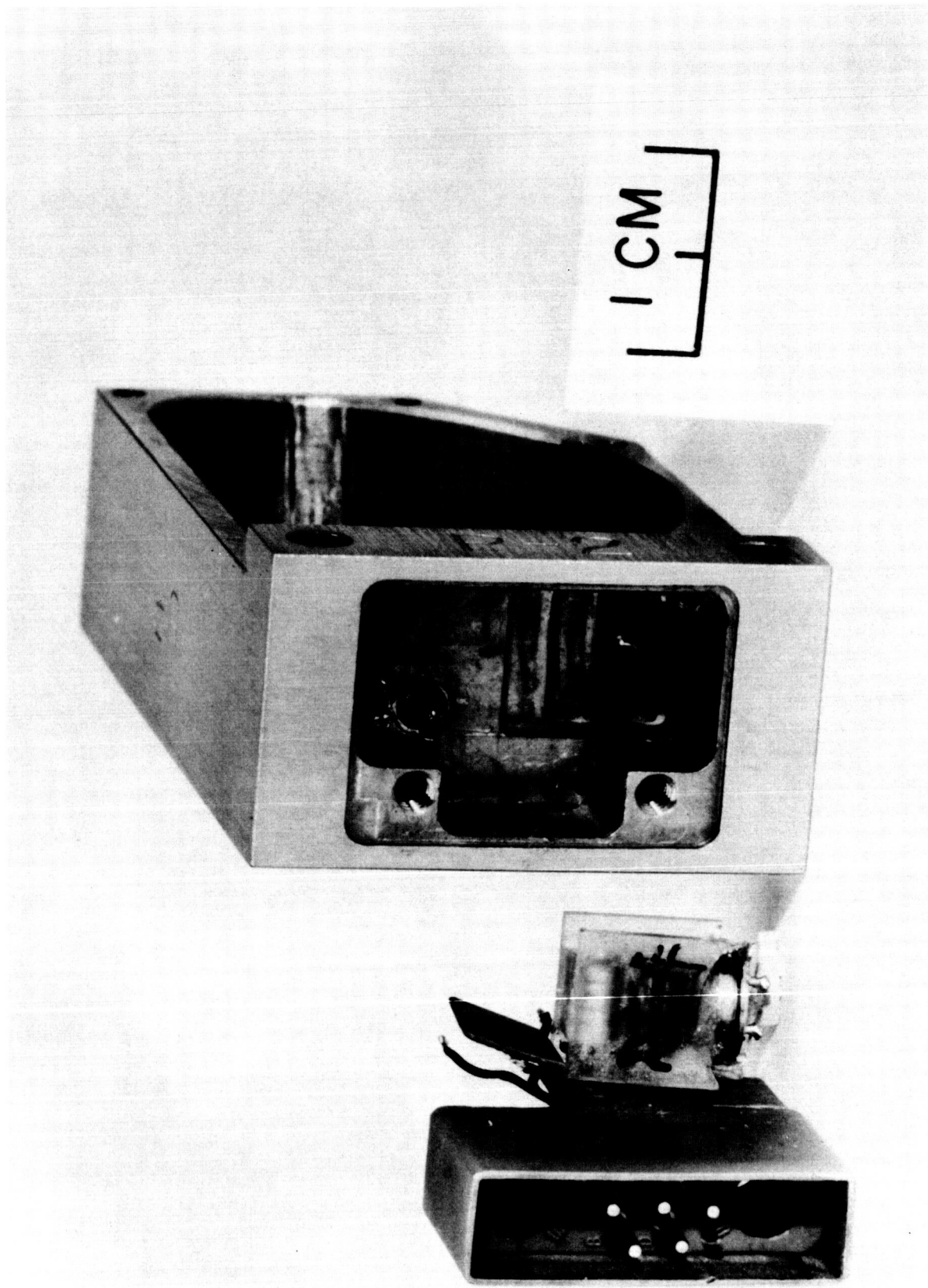


Figure 10.- Case, rear view with connector and preamplifier.

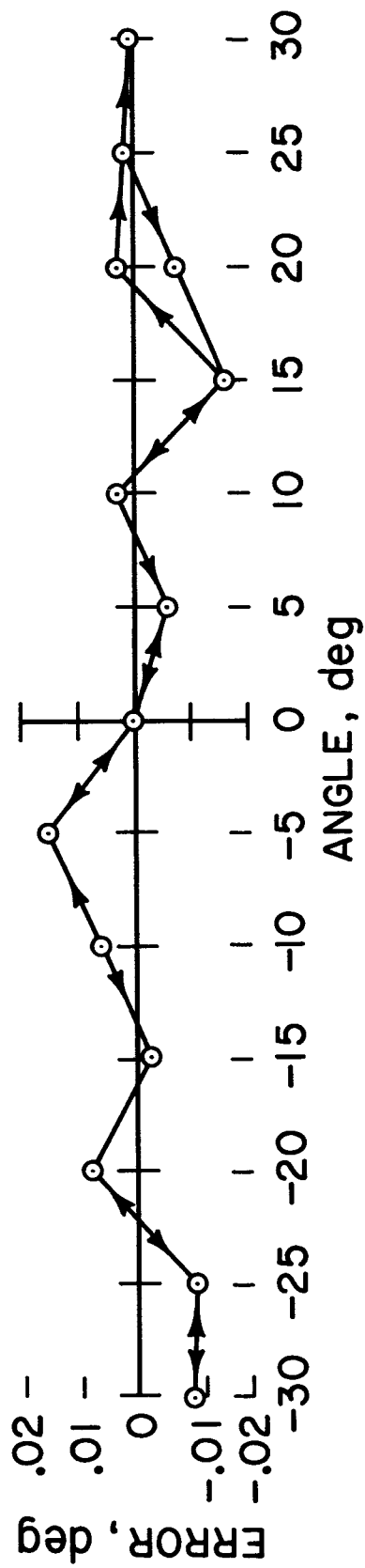


Figure 11.- Angle transducer system error curve.